MEBT Chopper Target Final Design Review

Tarik Saleh, Daryl Oshatz, Yoshy Minamihara

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1.0 Overview

The SNS Front End Medium Energy Beam Transport (MEBT) contains a chopper which deflects intense beam pulses into the MEBT Chopper Target. At a frequency of 60 Hz, a one millisecond pulse of 8400 watts of power hits the target, followed by a 15.7 millisecond cooling period. Although the average thermal power delivered to the beamstop is only 500 watts, the beam is highly focused. The high power density (over 300 kilowatts per square centimeter) of the beam pulses results in highly localized and cyclical surface stresses and temperature rises. The beam has a total cross-section approximately 2 cm wide by 1 cm tall, with the bi-gaussian power distribution depositing most of the power over a very small area. Previous analysis suggested that a water cooled target with a normally incident beam would not survive. The Chopper Target is, therefore, rotated 75 degrees off of the beam normal (x) axis, decreasing the heat flux on the target surface. A network of narrow water cooling passages located within one millimeter of the incident surface keeps peak stresses well within reasonable design limits.

Fabrication Summary	
Faceplate Material	Moly TZM
Faceplate Maching	Plunge EDM
Backplate Material	Moly TZM
Backplate Machining	Plunge EDM
Braze Material	Palcusil 25
Vacuum Air Guard	NO

Cooling Channel Summary		
Channel Width	1	mm
Channel Height	4	mm
Channel Area	4	mm^2
Total number of Channels	48	
Number of Passes	4	
Channels/Pass	12	

2.0 Materials Considerations

Conventional beamstop materials, such as copper and glidcop, have been avoided due to radiation activation concerns (at 2.5 MeV the ion beam would produce neutrons in copper). Molybdenum TZM (99.4% Mo, 0.5% Ti, 0.1% Zr) has been selected as the material for the MEBT Chopper Target because of its high fatigue strength, thermal conductivity, and resistance to sputtering.[1]

Materials properties used for thermal and stress analysis of the beamstop correspond to those described in ASTM 386-363, the specification for vacuum-arc-cast molybdenum TZM alloy. The material should be in the stress relieved (SR) condition. Recrystallized TZM is significantly weaker than SR TZM, and is not suitable for this beamstop design. Table 1.1 summarizes the ASTM standard.

Arc cast or PM		per ASTM B 386-363		estimated
.5-1" plate		Room TEMP		200C
		Yield	UTS	Yield
		MPa	MPa	
Stress Relieved		655	760	600
Recrystallized		310	515	250

Table 1.1: Mechanical Properties of TZM

3.0 Fabrication Details

The target assembly consists of a faceplate and a backplate which are brazed together. Forty-eight 1 mm wide by 4 mm deep cooling channels are cut in the back side of the faceplate using plunge EDM.

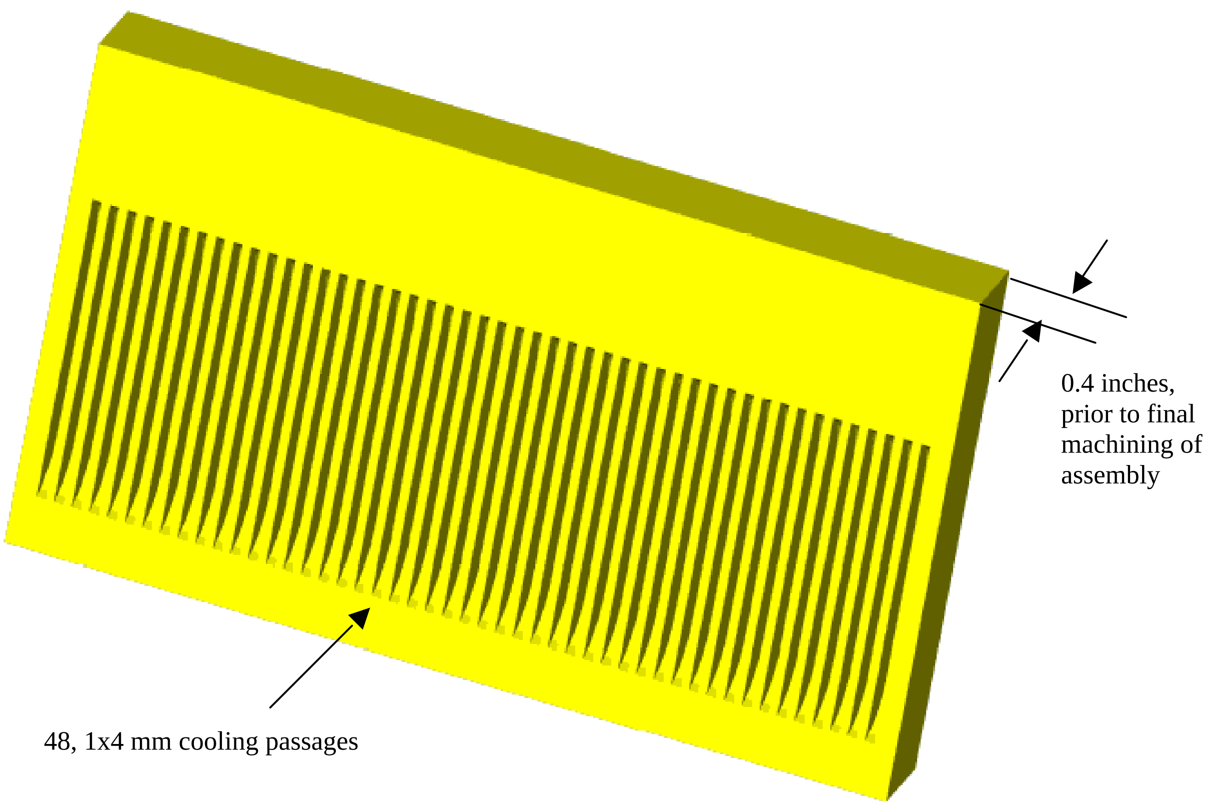


Figure 1: **Target Faceplate prior to brazing.**

A series of plenums in the backplate, similarly cut using plunge EDM, redirects the flow such that the cooling water makes four passes over the target area between the inlet and outlet.

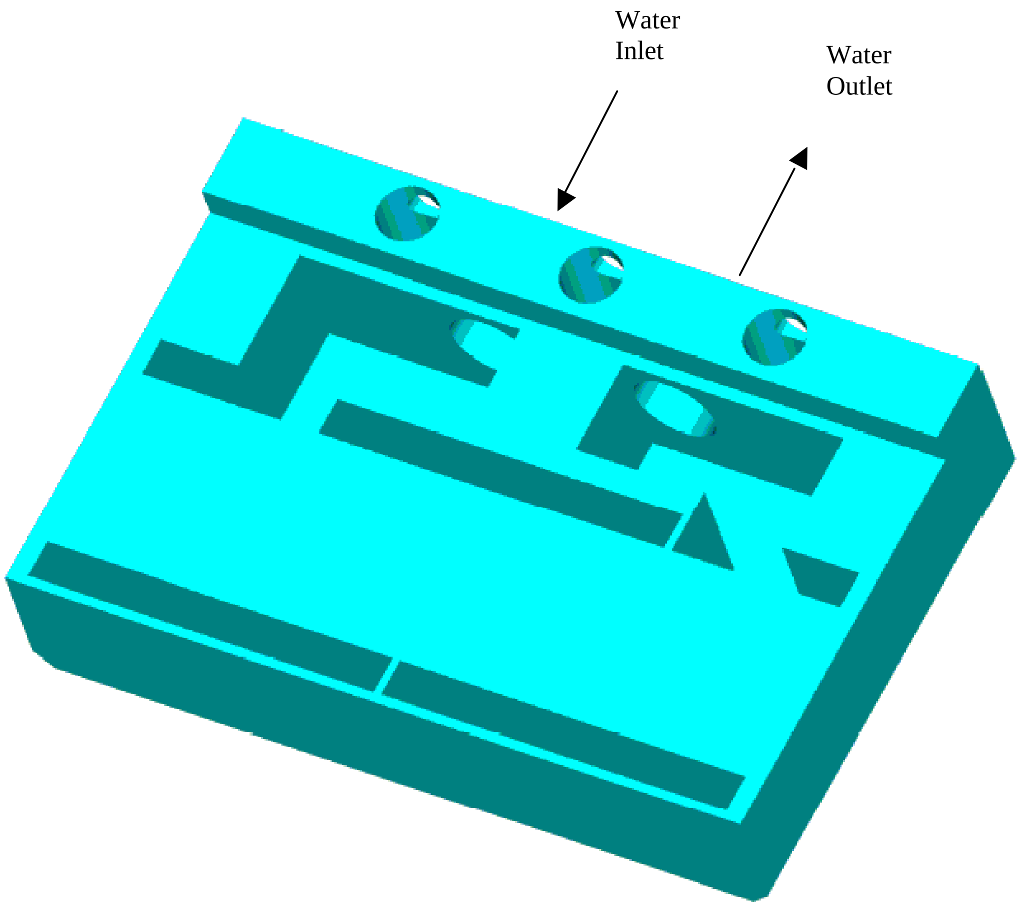


Figure 2: **Target Backplate**

The faceplate and backplate will be brazed together using the braze filler metal Palculsil 25 in foil form. The faying surfaces of the braze joint will be ground prior to machining to ensure uniform contact. To prevent warping during the braze operation, the faceplate will be machined out of 0.4 inch thick plate. The final thickness of the plate, 0.197 inches, will be achieved with a wire EDM cut made to the assembly after brazing. This cut, made to the front surface of the faceplate, will also create the round on the bottom of the faceplate (the round renders the hotwall thickness roughly uniform at the ends of the cooling channels).

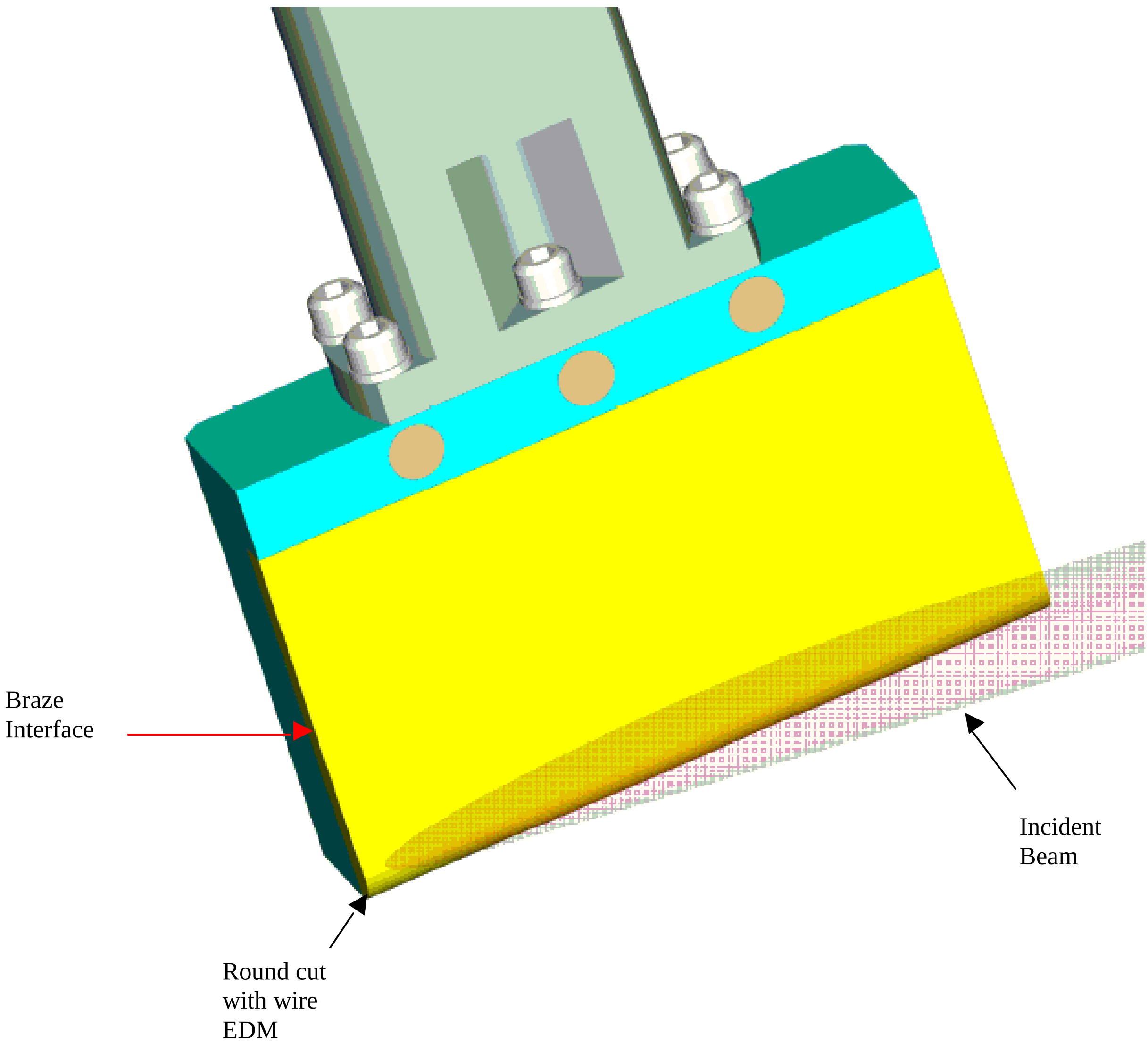


Figure 3: Target Assembly

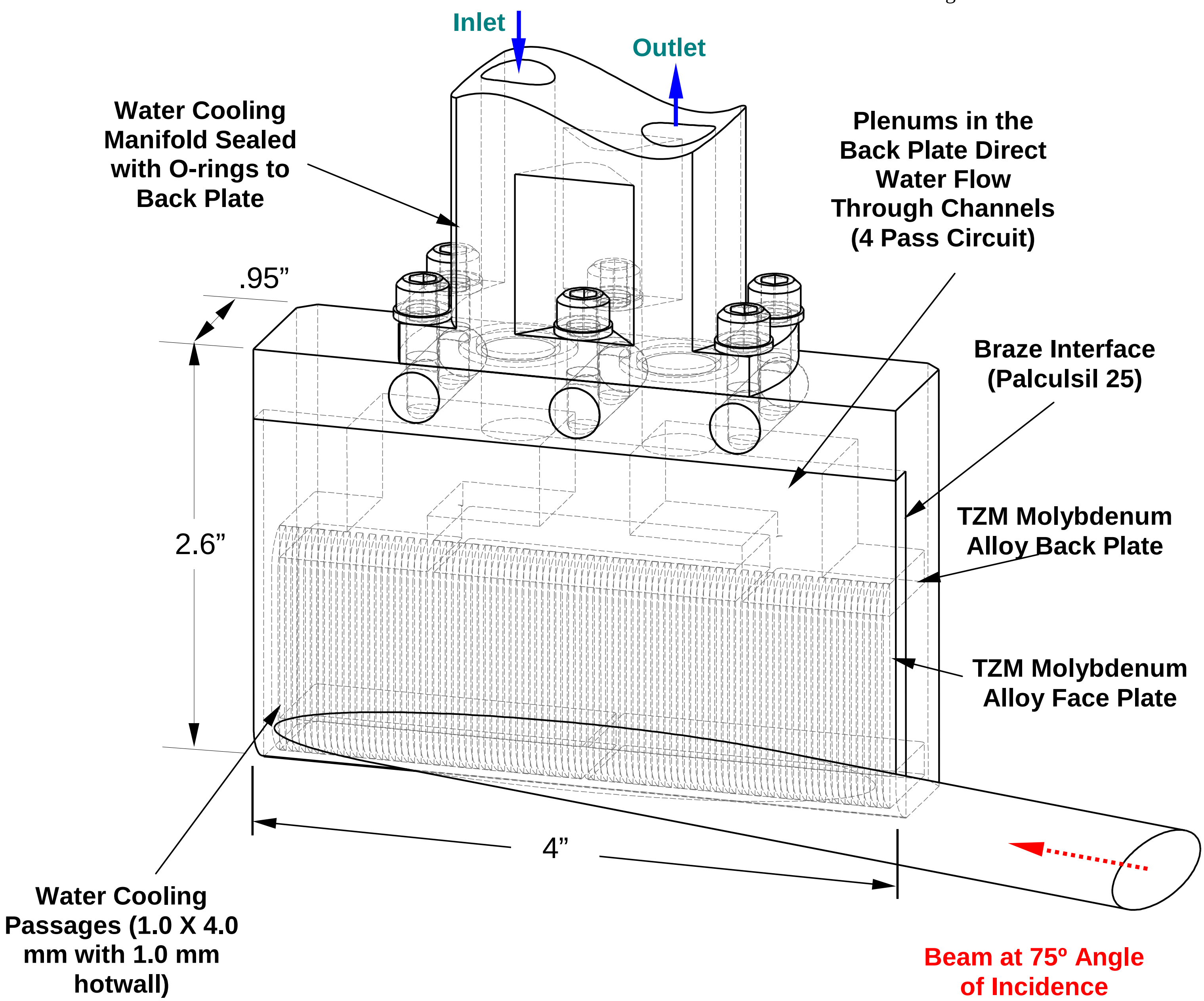


Figure 4: **Overall Target Dimensions**

4.0 Finite Element Analysis

The chopper target was modeled using ANSYS (version 5.5.2- see input code in Appendix E). The model consists of a Molybdenum TZM faceplate attached to a molybdenum TZM backing plate. There are 1 x 4 mm cooling channels located 1 mm below the incident surface. The beam stop is tilted at 75° off of the beam normal (x) axis. The power distribution is applied as a bigaussian distribution with a σx of 3.57 mm and a σy of 1.58 mm. The bulk water temperature is assumed to be 33°C.

The thermal transient analysis considers 1.0 msec long beam pulses arriving at 60 Hz (every 16.7 msec). The other time structure in the beam is on the nsec scale (50 nsec triangular pulses spaced 195 nsec apart and arriving every 841 nsec). The 8.4 kW average power applied in this model during the 1msec pulse is 6 percent (50 nsec / 841 nsec) of the peak power of 140 kW (2.5 MeV x 56 mA =140 kW). Previous FEA studies of this type of target showed that peak stresses resulted at the end of 60 Hz millisecond scale pulses, rather than during nanosecond scale pulses. Based on these previous results, the transient model includes nanosecond pulses by averaging peak power over 1.0 msec. An average power of 500W is applied to “normalize” the target.. This simulates a single millisecond scale burst of power on a target that has been in operation at steady state.

Additional bursts of power were applied to simulate 10 pulses, to verify the validity of the steady state approximation.

TZM’s material properties are summarized in table 1.1.
Data for the fatigue limit in pure molybdenum, seventy percent of ultimate tensile strength, should approximate that of molybdenum TZM alloy. This suggests that the fatigue limit should be roughly 420 MPa at 200°C.

Table 4.2 summarizes the results of the analysis, the factor of safety (FOS) in comparison to the fatigue limit is given.

	Surface temp, °C	wet wall temp °C	Surface stress MPa	FOS	Braze interface stress, MPA	FOS
steady state	101	86				
After 1 millisecond	206	110	271	1.6	62	6.7
After cooling period	89	82				

Table 4.1

ANSYS contour plots follow.

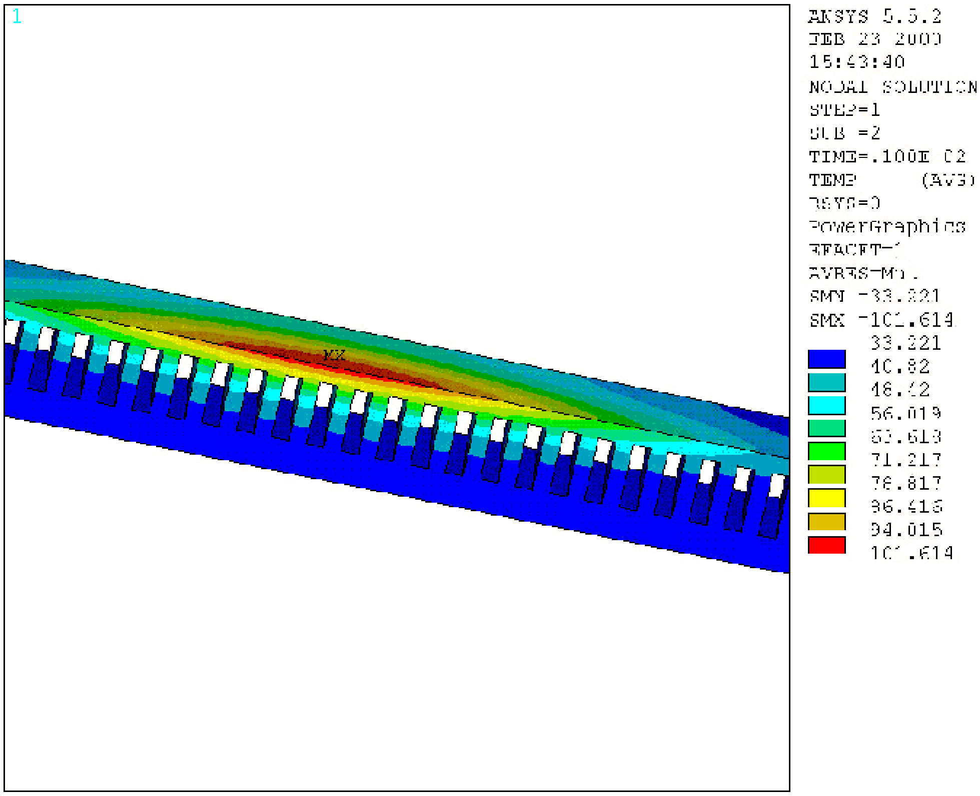


Figure 5: The ANSYS result for the first load step: the application of a 500W steady state power load. The peak temperature of 101.8°C is on the surface.

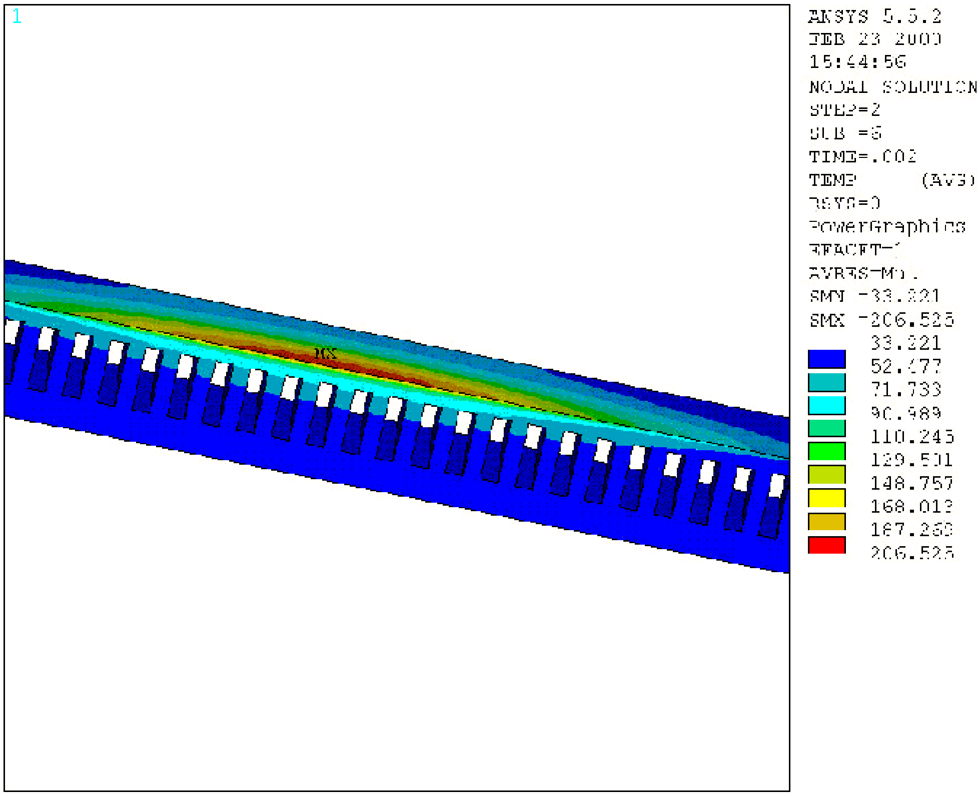


Figure 6: The ANSYS thermal result of the second load step, at the end of the 1 millisecond burst of 8.4kW. The peak temperature is 206°C on the surface

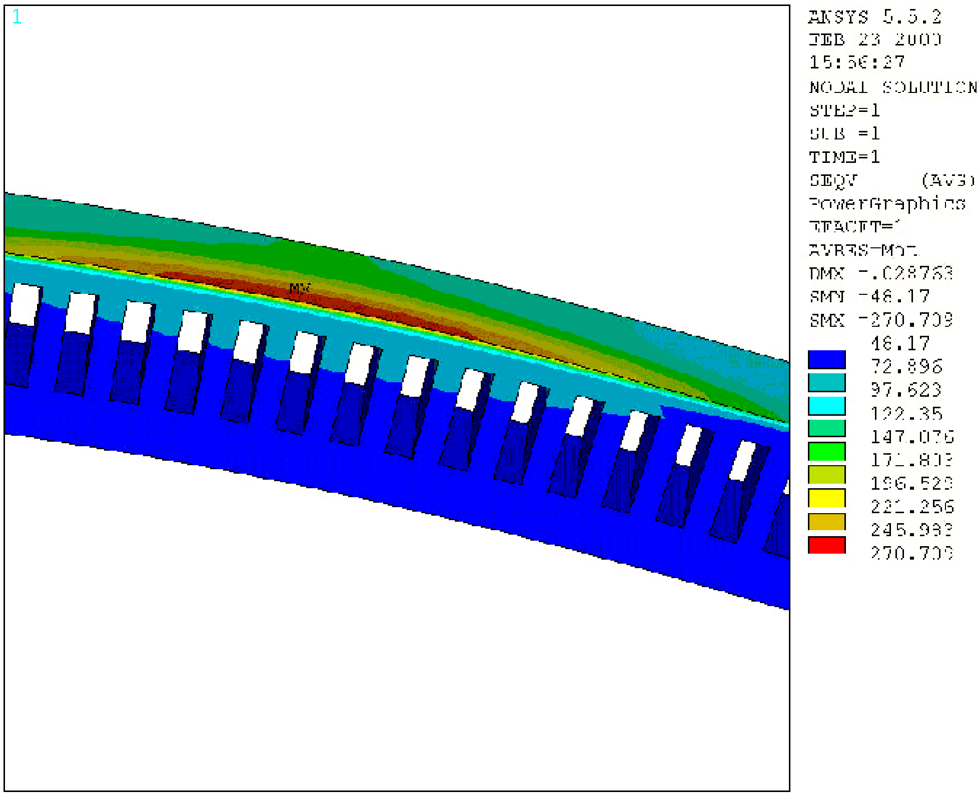


Figure 7: Von Mises stress in the beamstop immediately after the first millisecond pulse of power. The maximum Von Mises stress is 270 MPa and is mostly planar stress on the incident surface of the beamstop. The stress at the braze joint interface is 61 MPa.

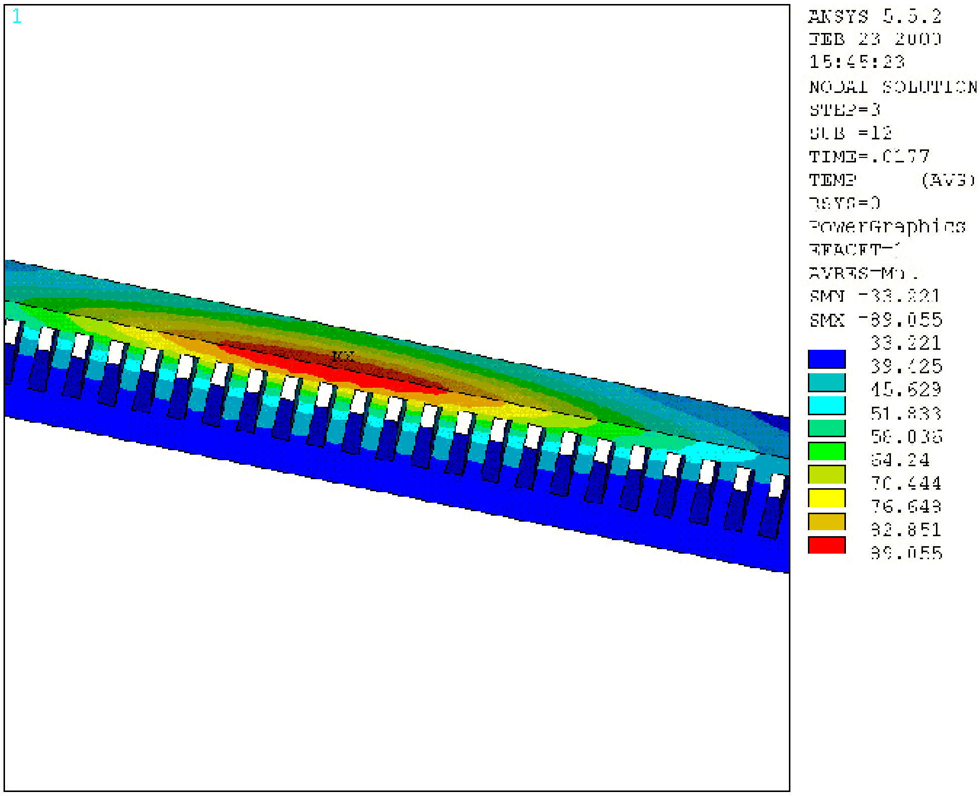


Figure 8: The result of the third load step, after the 15.7 millisecond cooling period. The peak surface temperature has fallen to 89°C.

Single Load Step:

Figure 9 is a detailed cooling curve following the first millisecond pulse, after the target is normalized (500 W applied steady state). The temperature falls to the initial steady state value within the first half (7 to 8 milliseconds) of the cooling period.

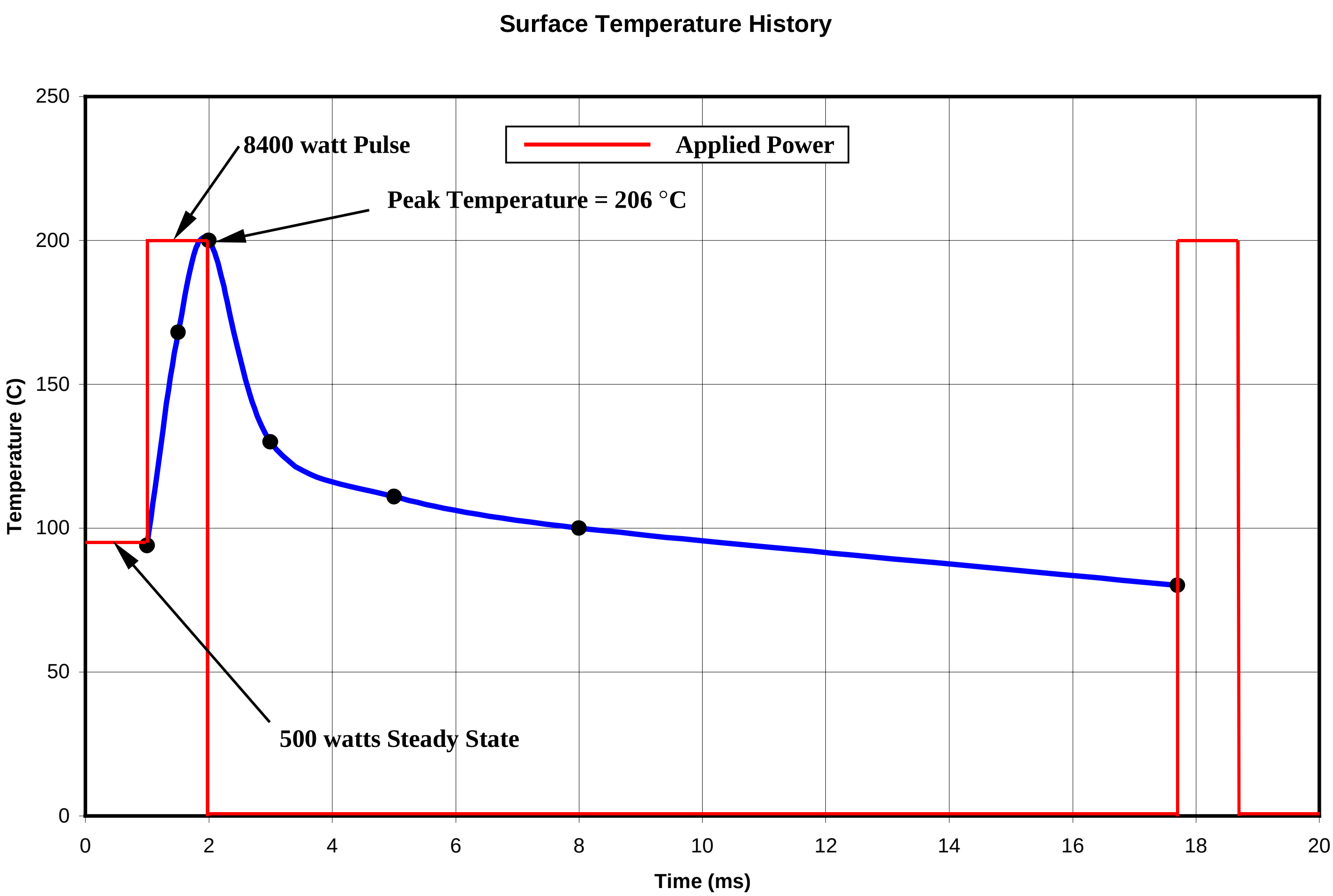


Figure 9: Heating and Cooling Curve

Multiple Load Steps:

The practice of applying a steady state load to model the chopper target in operation is somewhat conservative. With slightly different material parameters than the final model, an analysis was created to model a steady state load followed by 10 pulse cycles. The highest temperature was achieved after the first millisecond burst and fell with each successive cycle. This shows that the initial steady state approximation yields a slightly higher temperature than the operational steady state.

In this model the peak temperature was 205°C. The peak temperature fell 10°C over the next 10 cycles.

Figure 10 is a plot of the temperature in degrees centigrade reached after each millisecond pulse and 15.7 millisecond cooling period vs. time in seconds.

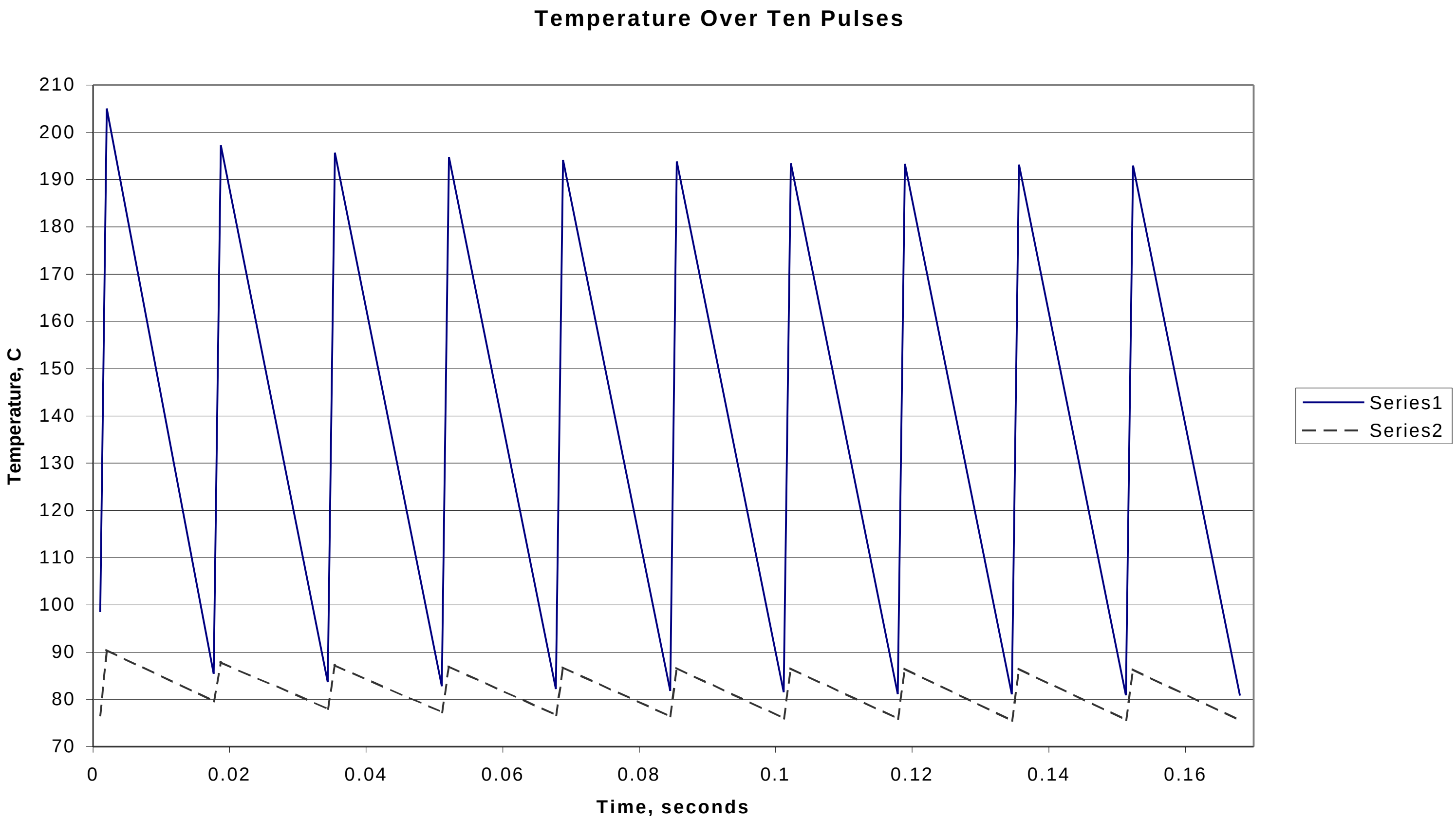


Figure 10: Series one represents the peak temperature on the surface during the 10 cycles, series two represents the wet wall temperature.

5.0 Brazing Test

In order to evaluate possible braze filler metals and cleaning techniques, a series of brazing tests were undertaken. Brazing coupons were wire EDM out of .150" TZM plate. Each half coupon was brazed to another coupon along the centerline, giving a .075 in^2 braze interface perpendicular to the pulling direction. The samples were placed in a brazing fixture with a weight on top during brazing. (see Appendix B for coupon dimensions and brazing fixture) The samples were tested on a tensile machine and the failure load was recorded. A successful braze was one that broke in the TZM metal, rather than in the brazing material.

Three brazing alloys were chosen to test the strength of the TZM-TZM brazement: Palcusil 25, Cusil ABA and Silver ABA. The brazing materials were chosen based on literature on TZM brazing **[2]** and brazing experience at LBNL. Each brazing alloy was to have three coupons brazed in a hydrogen furnace and three more brazed in a vacuum furnace. There were some problems with the hydrogen atmosphere in our furnace that led us to abandon our hydrogen test.

The main obstacle in brazing molybdenum-TZM alloys is the molybdenum and titanium oxide layers that form on the surface. These oxides are difficult to remove and prevent good wetting of the brazing material. A rigorous cleaning method was specified for our test coupons immediately (within 2 hours) prior to the brazement (appendix C). The ABA alloys were chosen because they contain a small (less than 2%) amount of titanium which actively attacks the oxide layer and cleans the surface so the braze material can flow better. Unfortunately, the titanium also makes the brazement extremely sensitive to furnace cleanliness. The first runs in vacuum with the ABA alloys resulted in poor wetting and discoloration in the filler metal. We believe this is due to atmosphere related contaminants. At this time, only the palcusil 25 brazing samples were suitable for testing.

Table 5.1 summarizes the results of the Palcusil 25 brazing tests:

Specimen	Joint Area	Failure Load	Stress
	in^2	lbs	MPa
T1	0.0759	4000	363.6
T2	0.0773	4128	368.6
T3	0.0771	4152	371.4

Table 5.1: Braze Test Results

In two of the three samples, T1 and T3 (figures 11 and 13, respectively), the molybdenum TZM base metal broke before the filler metal. Sample T2 (figure 12) appeared to break in the filler metal. The breaking stresses in all three cases were far higher than that at the braze interface between the chopper target faceplate and backplate (61 MPa). Sample T1 was loaded in an Instron machine with a pin holding the sample. The sample broke around the hole, indicating that the stress concentration at the hole was far greater than the tensile strength of the TZM. The subsequent tests were run in an Instron machine with diamond jaws. These jaws imparted a bending moment in addition to the tensile force, causing the breaking stress to appear lower than the expected UTS of the parent material.

Figure 11

Figure 12

Figure 13

6.0 Fluid Mechanics Calculations

The design of the Chopper Target cooling passages was based on a design for thermal absorber devices used at the Advanced Light Source at LBNL **[3]** The narrow, wide cooling passages maximize the convective film coefficient for a given flow rate. A flow velocity of fifteen feet per second was selected as the nominal operating point for the target. At this flow rate cavitation and wear in the cooling passages should not be a concern. This flow velocity results in a volumetric flow rate of 3.6 gallons per minute with a pressure drop of roughly 10 PSI in the target and manifold assembly. The temperature rise in the cooling water is less than one degree Celsius. Table 6.1 summarizes the fluid mechanics calculations, Appendix D contains more in depth calculations.

Chopper Target Design Parameters		
1. Channel Details		
Channel Width	0.04	in
Channel Height	0.16	in
Channel Area	0.0024	sq.in
Flow Velocity in Channel	15	feet per second
Reynolds Number	8,639	
Film Coefficient (-25%)	1.99	W/sq.cm-K
Volume Flow Rate per Channel	0.299	gallons per minute
Channel Length	1.4	in
2. Manifold / Plenum Details		
Total Volume Flow Rate	**3.59**	gallons per minute
Total Number of Channels	48	
Number of Groups in Series	4	
Number of Parallel Channels per Group	12	
Plenum Depth	0.7	in
Plenum Width (to channels)	0.2	in
Plenum Flow Area	0.14	sq.in
Plenum Flow Velocity	8.23	feet per second
Inlet/Outlet Plenum Width	0.5	in.
Header Inlet/Outle Diameter	0.438	in
Header Length	12	in
Header Flow Velocity	7.64	feet per second
3. Pressure Drop Estimates		
A. Channels (in straight sections)		
Hydralic Diameter	0.064	in
Friction Factor (Blasius Approximation)	0.033	
Total Pressure Drop	4.3	psi
B. Channel Entrances and Exits		
Estimated K for Entrances and Exits	1.25	
Number of Entrances per Circuit	4	
Number of Exits per Circuit	4	
Total Pressure Drop	4.54	psi
C. Header / Manifold		
Flow velocity in Tubes	7.64	feet per second
Pressure Drop in Tubes	0.52	psi
Flow velocity in Inlet/Outlet Plenums	3.291	feet per second
Estimated K for 90 Degree Bends	1	
Number of 90 degree Bends	4	
Pressure Drop in Plenums	0.291	psi
Total Pressure Drop	0.81	psi
Total Pressure Drop of Assembly	**9.68**	**psi**
4. Temperature Rise in Cooling Water		
Average Power on Target	500	W
Temparture Rise in Cooling Water	0.53	degrees C

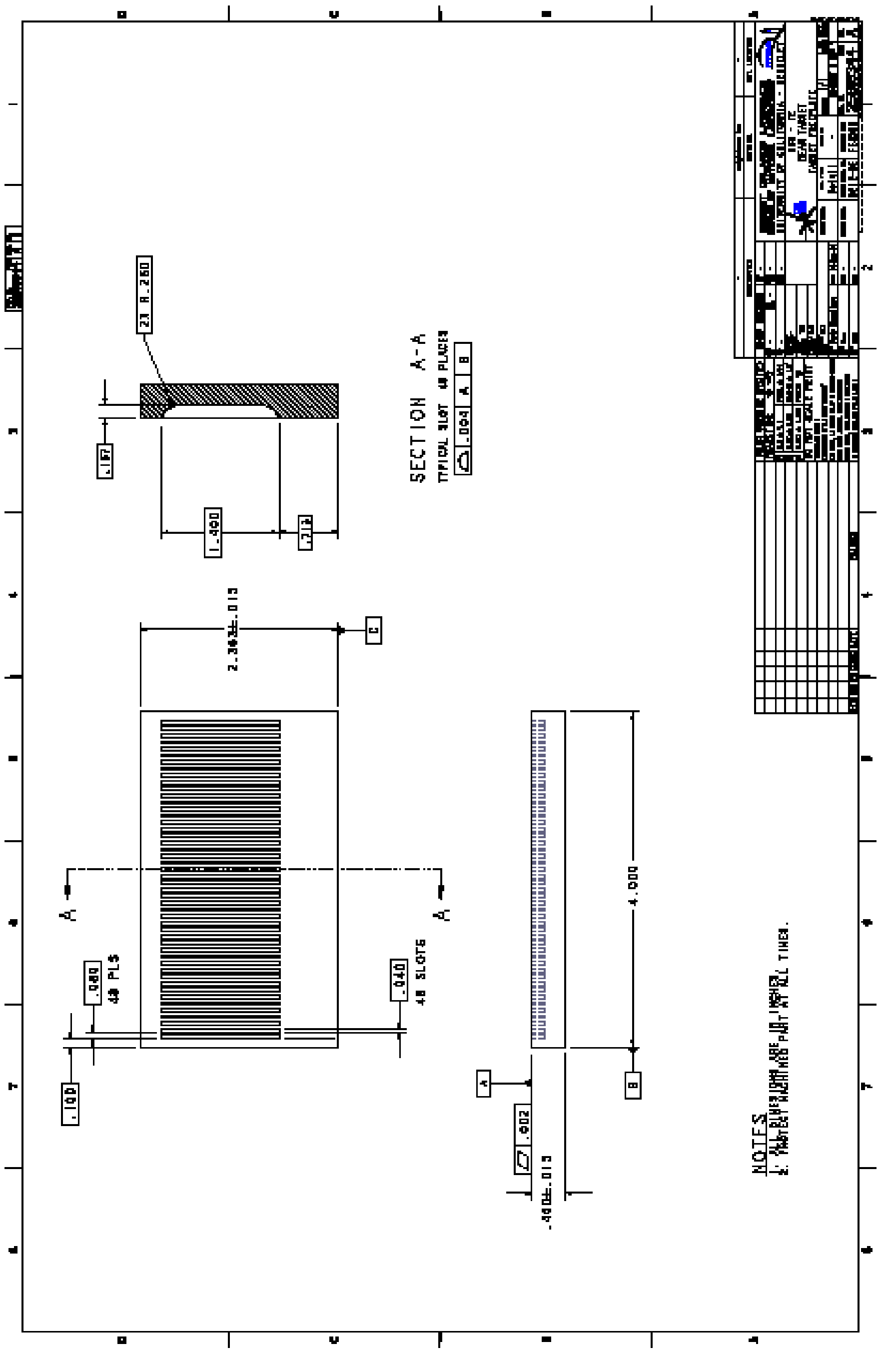
Table 6.1: Fluid Mechanics Summary

7.0 Summary

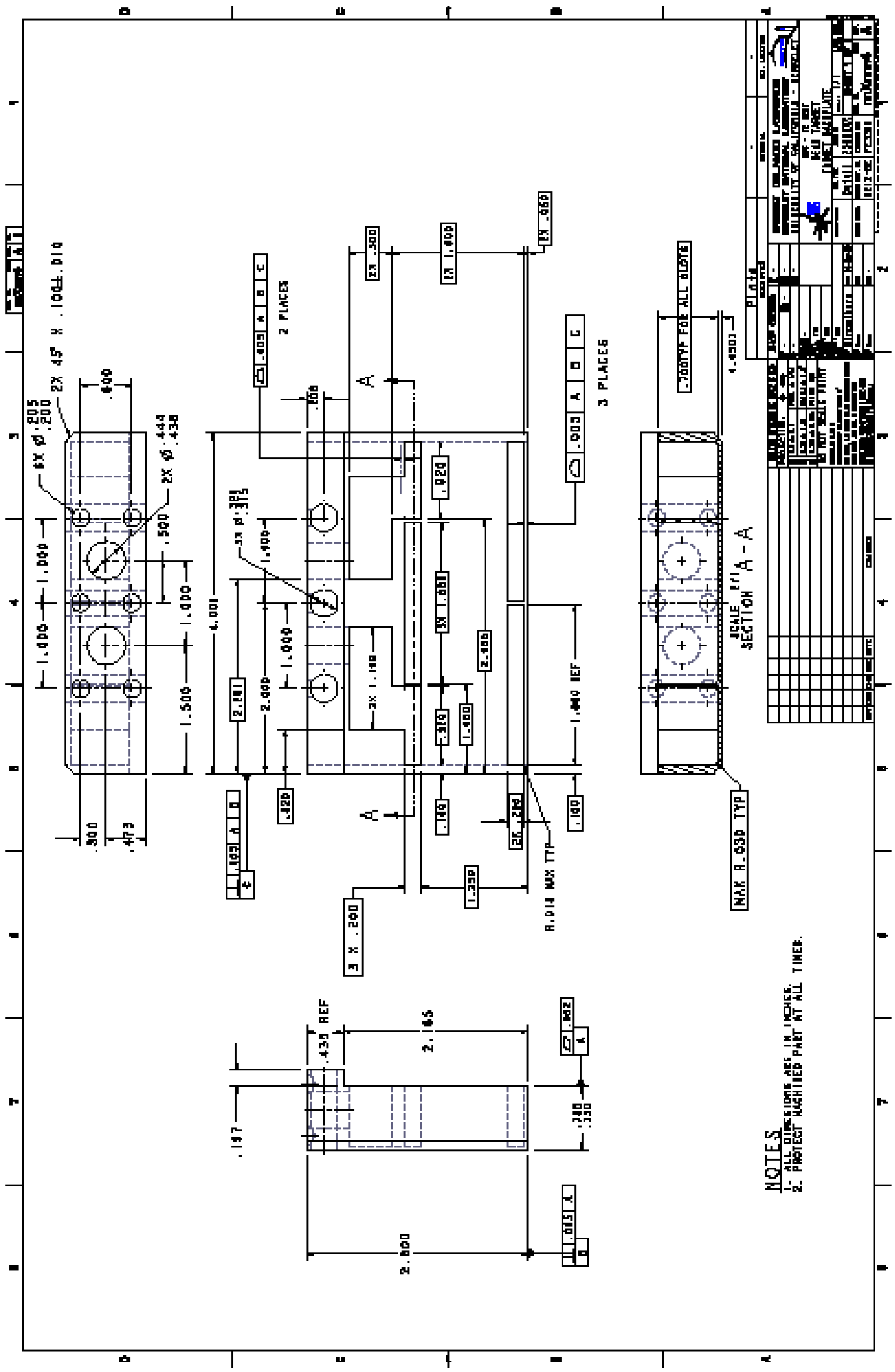
The MEBT Chopper beam pulses will result in peak surface stresses well within the design limits of the Chopper Target material, TZM. Finite element analysis predicts a peak surface temperature of approximately 200°C. At this temperature, the endurance limit of TZM is roughly 1.6 times the cyclical, peak stress predicted by the model. A feasible brazing process has been selected and tensile tests indicate that the brazed interface in the target will have a strength far in excess of that required during operation.

Appendix A

Mechanical drawings face and backplate

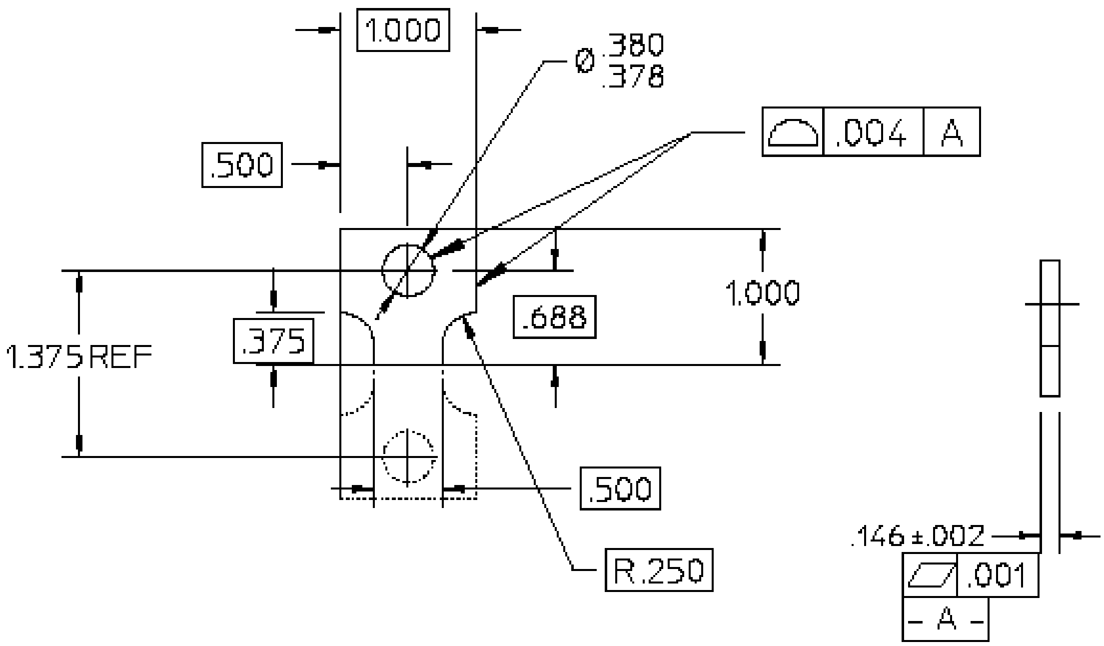


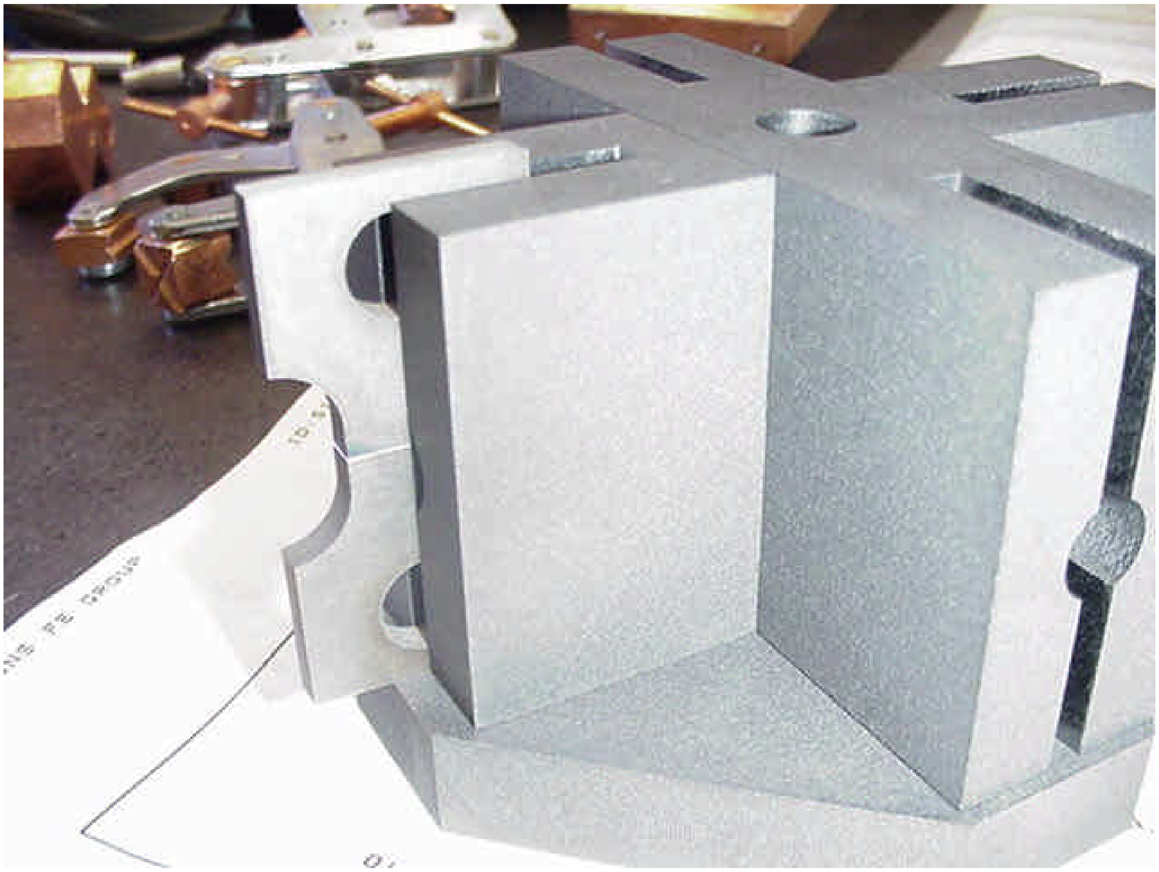
Faceplate Drawing



Backplate Drawing

Appendix B
Mechanical drawings of tensile samples




Tensile sample in the brazing fixture. Three coupons were brazed in each fixture, the fourth slot was left open so the weight would compress the three assemblies.


Fixture with weight on top

Appendix C

Cleaning procedure for molybdenum TZM alloy

Material to be placed in the furnace within two hours of cleaning.

909 cleaner 15 minutes
DI water Rinse
HF Acid 2 minutes
Tap water rinse
Electropolish 2 minutes:
    6 volts 128F
    HCl 50% Dip

909 cleaner
DI water rinse
DI water rinse
Hot water 160F rinse

Nitrogen Airdry.

Appendix D

Fluid Mechanics Calculations

General Equations for Heat Transfer 6/15/00
Rectangular cross-section ("D")

HYDRAULIC DIAMETER Dh = 4A/P

Channel L x W [in.]	A [sq.in.] *	P [in.]	Dh [ft]	Dh [in.]
0.040	6.40E-03	0.40	0.005	0.064
0.160				
Tube Dia [cm]	A [sq.cm]	P [cm]	Dh [cm]	
0.102	0.0413	1.02	0.163	
0.406				

FLOW RATE q = VA
FLOW RATE Q [gal/min] = (q [cu.ft/sec])(60 [sec/min])(7.479 [gal/cu.ft])

V [ft/sec] *	A [sq.ft]	q [cu.ft/sec]	Q [gal/min]	# of Channels
15.00	4.44E-05	6.67E-04	**0.299**	**12**
			3.590	GPM total/circuit

REYNOLDS NUMBER

Re = (V [ft.sec] x D [ft] x rho [lbm/cu.ft]) / mu [lbm/ft.sec]

V [ft/sec]	Dh [ft]	rho [lbm/cu.ft] * (default @25 deg.C)	mu [lbm/ft.sec] * (default @25 deg.C)
1.50E+01	5.33E-03	6.22E+01	6.14E-04

Re = 8.10E+03

CONVECTION HEAT TRANSFER
Film Coefficient hf = (k/Dh) x Nu

Conductivity k [W/cm-K] (default @25 deg.C)	Hydraulic. Dia. Dh [cm]	Prandtl Pr (default @25 deg.C)
6.09E-03	1.63E-01	7.50E+00

per Sieder and Tate Eqn's (+/- 25%) !!!

Nu	Re	hf [W/sq.cm-K]	hf +/- 25%	
TURBULENT		TURBULENT Re > 3000		
(assumes mu/muW = 1)			**3.31**	
70.76	8099	**2.65**	**1.99**	W/sq.cm.-K
		0.0265	**0.0199**	W/sq.mm.-K

LAMINAR
(assumes mu/muW = 1)

Nu	Tube Length	hf [W/sq.cm-K]	hf +/- 25%	
	L [cm]	LAMINAR		
	170.70	Re < 2000		
	Dh/L		(assumes Re x Pr x Dh/L > 10)	
	0.001	5.78E+01	0.34	
7.19	per S. & T.:	**0.27**	0.20	W/sq.cm.-K
6.08	alternate:	**0.23**	0.17	W/sq.cm.-K
		0.0023	**0.0017**	W/sq.mm.-K

LINEAR INTERPOLATION

Find f(x):	
x1	20.0000
x	35.0000
x2	40.0000
f(x1)	6.02E-03
f(x2)	6.31E-03
f(x)	6.24E-03

PROPERTIES OF WATER

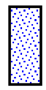
Temperature [deg.C]	Prandtl No. Pr	Pr^(1/3)	Pr^.4
20.0	8.56	2.05	2.36
25.0	7.50	1.96	2.24
40.0	4.33	1.63	1.80
60.0	3.41	1.51	1.63
80.0	2.49	1.36	1.44

Temperature [deg.C]	Density rho [lbm/cu.ft]	Viscosity mu [lbm/ft.sec]	Conductivity k [W/cm-deg.C]
20.0	62.3	6.73E-04	6.02E-03
25.0	62.2	6.14E-04	6.09E-03
40.0	62.0	4.39E-04	6.31E-03
60.0	61.4	3.14E-04	6.53E-03
80.0	60.7	2.38E-04	6.69E-03

WATER TEMPERATURE RISE
Delta-T [deg.C] = .0038 x P [W] / Q [gal/min]

P [W]	Q [gal/min]	Delta-T [deg.C]
500	3.59	**0.53**

Pressure Drop:

$\Delta p = \rho * f * L/D_h * v^2/2$	Δp	pressure drop	
	ρ	density	
	f	friction factor	
b 	L	passage length	
	Dh	hydraulic diameter =	2*a*b/(a+b)
a	v	flow velocity	

Blasius Friction Factor

f =.316/Re^.25	f	friction factor	Turbulent flow in smooth pipes
	Re	Reynolds number=ρvD/μ (only for ε/D≅0, 4e3 < Re < 1e5)	

Pressure Drop Due to Loss Coefficient, K_L

Δ**p = K_L*v^2/2***ρ/144	Dp	pressure drop (psi)
	v	flow velocity (ft/s)
	r	density (slugs/ft^3)

Properties of Cooling water

Ave.Bulk Temp:	Tave =	80	F		
Specific Heat:	Cp =	4.177	kJ/kg/K		
Density:	80F ρ =	1.934	slugs/ft^3	1000	kg/m^3
Dynamic Viscosity:	80F μ =	1.8E-05	lb-s/ft^2		
Conversion Factor:	1 GPM =	2.23E-03	ft^3/s		

Pressure Drop in Channels

passage width, a =	0.04	in		
passage height, b =	0.16	in		
D_h =	0.064	in =	0.005333	ft
passage length, L =	1.4	in	0.116667	ft
Flow Velocity, v =	15	ft/s		
Re =	8,639			
f =	0.0328			
Pressure Drop, Δp =	1.0834	psi (per passage)		
# Passages per Group =	12			
# of Groups in Series =	4			
Total Pressure Drop =	**4.33**	**psi**		

Pressure Drop in Plenums over Channels

plenum width =	0.2	in		
Plenum depth =	0.7	in		
Plenum Flow Area =	0.14	in^2		
Total Flow Rate =	3.5899	GPM =	8.00E-03	ft^3/s
Flow Velocity =	8.23	ft/s		
Est. K_L for entrances and exits	1.25			
Number of Entrances per Circuit	4			
Number of Exits per Circuit	4			
Pressure Drop	**4.545**	**psi**		

Pressure Drop in Header Tubes

flow diam.	0.438	in =	0.0365	ft
Flow area	0.150673925	in^2 =	0.001046	ft^2
Flow velocity	7.64	ft/s		
Reynolds Number	30129			
Friction Factor	0.0240			
Header Length	12	in		
Flow Length	2	ft		
Pressure Drop in Tubes	0.515694341	psi		
Pressure Drop in Header Plenums				
plenum width =	0.5	in		
Plenum depth =	0.7	in		
Plenum Flow Area =	0.35	in^2		
Total Flow Rate =	3.5899	GPM =	8.00E-03	ft^3/s
Flow Velocity =	3.29	ft/s		
Est. K_L for 90 degree bends	1			
Number of 90 degree bends	4			
Pressure Drop in Plenums	**0.2909**	psi		

Appendix E

ANSYS Thermal Input File

```
MPTEMP,1,27,127,202,500,1000                !Temp. in °C

! Material #3: Molybdenum TZM Properties
mpdata,alpx,3,5.08e-6,5.12e-6,5.23e-6,5.37e-6,5.53e-6        !mm/mm/K  Thermal expansion coeff
mpdata,kxx,3,1,.127,.125,.120,.115,.110                      !W/mm/K    Thermal conductivity
mpdata,c,3,1,272,272,272,275,285                             !J/kg/K       Heat capacity
mp,dens,3,10.22e-6                                           !kg/mm^3   Density
mpdata,ex,3,1,284e3,274e3,264e3,236e3,                       !N/mm^2  Modulus
mp,nuxy,3,.33                                                !Poissons ratio

!TZM data from Karditsas, P.J., Baptiste, M-J.  Thermal and Structural Properties of Fusion related
!Materials  available at http://www-ferp.ucsd.edu/PROPERTIES/
```

ANSYS input to build model

```
/prep7
/input,materials,txt,G:\Ansysdata\molystop

!All dimensions in mm
sx=3.86*3.57      ! sigma x /cos(75)
sy=1.58

xc= 6*sx   !total width of model in x

v=2*xc  ! number of division per length in x

yc= 11.525  !
w=yc  !number of division per total height
mt=0.1  !thin moly layer
hw = 1   !hot wall
d=3*sy  !total y dimension of model
dd=2*d   ! number of division per length in x


n=41  !#of channels
a=1   !channel width
b=4    !channel height

!locations in relation to hot surface

topc=mt+hw    !top of channel
bc=topc+b      !vottom of channel
fl=bc+2         !"floor", bottom of target

aa=((xc/(n+1))-(a/2))    !distance at either end of channels

bb=a                                      !channel width
cc=((xc/(n+1))-a)         !distance between channels

!build model

/VIEW, 1 ,1,2,3
/ANG, 1
```

```
k,,0,0,0
k,2,0,d
k,3,0,0,-mt
k,4,0,0,-topc
k,5,0,0,-bc
k,6,0,0,-fl

!lines to extrude by, #1-#4
l,1,3,5
l,3,4,5,10
l,4,5,b
l,5,6,(yc-hw-b)/2

*do,x1,xc/(n+1),xc-(xc/(n+1)),xc/(n+1)
k,,x1-(a/2),0
k,,x1+(a/2),0
*enddo
k,,xc,0

*do,x1,xc/(n+1),xc-(xc/(n+1)),xc/(n+1)
k,,x1-(a/2),d
k,,x1+(a/2),d
*enddo
k,,xc,d

!horizontal lines in x direction at y=0
ksels,s,loc,y,0,
ksel,r,loc,z,0,mt
*get,kpmin,kp,,num,min
*get,kpmax,kp,,num,max
*get,kpmon,kp,kpmin,nxth
*get,kpmox,kp,kpmax,nxtl
l,kpmin,kpmon
*do,kp1,kpmon,kpmox,
*get,kp2,kp,kp1,nxth
*get,kp3,kp,kp2,nxth
l,kp1,kp2
*enddo


allsel,all

!horizontal lines in x direction at y=d
ksels,s,loc,y,d,
ksel,r,loc,z,0,mt
*get,kpmin,kp,,num,min
*get,kpmax,kp,,num,max
*get,kpmon,kp,kpmin,nxth
*get,kpmox,kp,kpmax,nxtl
l,kpmin,kpmon
*do,kp1,kpmon,kpmox,
*get,kp2,kp,kp1,nxth
*get,kp3,kp,kp2,nxth
l,kp1,kp2
*enddo

allsel,all

!lines in y direction

*do,x1,xc/(n+1),xc-(xc/(n+1)),xc/(n+1)
ksel,s,loc,x,x1-(a/2)
*get,kpmin,kp,,num,min
*get,kpmax,kp,,num,max
l,kpmin,kpmax,dd
allsel,all
ksel,s,loc,x,x1+(a/2)
*get,kpmin,kp,,num,min
*get,kpmax,kp,,num,max
l,kpmin,kpmax,dd
*enddo
allsel,all
l,1,2,dd
ksel,s,loc,x,xc
```

```
*get,kpmin,kp,,num,min
*get,kpmax,kp,,num,max
l,kpmin,kpmax,dd
allsel,all

!LESIZE lines
!above channels
*do,x1,xc/(n+1),xc-(xc/(n+1)),xc/(n+1)
lsel,s,loc,z,mt,0
lsel,s,loc,x,x1
lesize,all,,,a/xc*v
allsel,all
*enddo

!between
*do,x1,xc/(n+1),xc-2*(xc/(n+1)),xc/(n+1)
lsel,s,loc,z,mt,0
lsel,s,loc,x,x1+(xc/(2*(n+1)))
lesize,all,,,v*((xc/(n+1))-a)/xc
allsel,all
*enddo

!left and right
lsel,s,loc,z,mt,0
lsel,s,loc,x,((xc/(n+1))-(a/2))/2
lesize,all,,,v*((xc/(n+1))-(a/2))/xc
allsel,all
lsel,s,loc,z,mt,0
lsel,s,loc,x,xc-((xc/(n+1))-(a/2))/2
lesize,all,,,v*((xc/(n+1))-(a/2))/xc
allsel,all

!create areas

!ABOVE CHANNELS
*do,x1,xc/(n+1),xc-(xc/(n+1)),xc/(n+1)
ksel,s,loc,z,0,mt
ksel,r,loc,x,x1-(a/2),x1+(a/2)
lslk,,1
*get,lmin,line,,num,min
*get,lmax,line,,num,max
*get,l1,line,lmin,nxth
*get,l2,line,lmax,nxtl

al,lmin,l1,l2,lmax
allsel,all

*enddo
allsel,all

!BETWEEN CHANNELS
*do,x1,xc/(n+1),xc-2*(xc/(n+1)),xc/(n+1)
ksel,s,loc,z,0,mt
ksel,r,loc,x,x1+(a/2),x1+(xc/(n+1))-(a/2)
lslk,,1
*get,lmin,line,,num,min
*get,lmax,line,,num,max
*get,l1,line,lmin,nxth
*get,l2,line,lmax,nxtl

al,lmin,l1,l2,lmax
allsel,all

*enddo
allsel,all

!TO THE RIGHT AND LEFT

ksel,s,loc,z,0,mt
ksel,r,loc,x,0,xc/(n+1)-(a/2)
lslk,,1
*get,lmin,line,,num,min
*get,lmax,line,,num,max
*get,l1,line,lmin,nxth
```

```
*get,l2,line,lmax,nxtl

al,lmin,l1,l2,lmax
allsel,all

ksel,s,loc,z,0,mt
ksel,r,loc,x,xc,xc-xc/(n+1)+(a/2)
lslk,,1
*get,lmin,line,,num,min
*get,lmax,line,,num,max
*get,l1,line,lmin,nxth
*get,l2,line,lmax,nxtl
al,lmin,l1,l2,lmax
allsel,all

!mesh the surface
et,1,55
asel,s,loc,z,0,mt
mat,3
amesh,all

et,2,70
type,2
asel,s,loc,z,0,mt

mat,3
vdrag,all,,,,,1
allsel,all
asel,s,loc,z,-mt,-mt

mat,3
vdrag,all,,,,,2,3,4
allsel,all

eplot
!clear area nodes&elements
asel,s,loc,z,0
nsla,s,1
esln,s,1
aclear,all
alls

!clear water channels
*do,x1,xc/(n+1),xc-(xc/(n+1)),xc/(n+1)
vsel,s,loc,x,x1
vsel,r,loc,z,-topc-b/2


vclear,all
alls
*enddo
eplot

!apply constraints
*do,x1,xc/(n+1),xc-(xc/(n+1)),xc/(n+1)
nsel,s,loc,z,-bc,-topc
nsel,r,loc,x,x1-a/2,x1+a/2

sf,all,conv,.0196,33   !Units are W/mm^2C (Film coeff. = 15,850 W/m^2C)

!d,all,temp,25
allsel,all
*enddo
```

Application of 500W power distribution

```
totnod=xc*d/(v*dd)
area=2*3.1415*sx*sy
avgpow=500
/VIEW, 1 ,,,1
/ANG, 1
/REP,FAST
```

```
!bigaussian distribution to nodes-avg power to equilibrilize
nsel,s,loc,z,0,mt
*get,nnodes,node,,count
*get,maxnode,node,,num,max
*get,minnode,node,,num,min
pave=avgpow/area*totnod
*do,cnt,minnode,maxnode


*get,xloc,node,cnt,loc,x
*get,yloc,node,cnt,loc,y
nsel,s,loc,z,0
nsel,r,loc,x,xloc
nsel,r,loc,y,yloc

*if,yloc,eq,0,then
f,cnt,heat,pave/2*exp(-(xloc-xc/2)*(xloc-xc/2)/(2*sx*sx)-yloc*yloc/(2*sy*sy))
*else
f,cnt,heat,pave*exp(-(xloc-xc/2)*(xloc-xc/2)/(2*sx*sx)-yloc*yloc/(2*sy*sy))
*endif

!nsel,u,node,,ct
!*get,cnt,node,cnt,nxth
!cnt=cnt+1
*enddo
alls


nsel,s,loc,z,0
allsel,all


!f,all,heat,0
allsel,all

t=.001
time,t
timint,off,all
lswrite,1
allsel,all
```

Application of 1 millisecond 8.4kW burst

```
/prep7


kbc,1

!bigaussian distribution to nodes burst number one
nsel,s,loc,z,0,mt
*get,nnodes,node,,count
*get,maxnode,node,,num,max
*get,minnode,node,,num,min
pave=avgpow/(.06*area)*totnod
*do,cnt,minnode,maxnode


*get,xloc,node,cnt,loc,x
*get,yloc,node,cnt,loc,y
nsel,s,loc,z,0
nsel,r,loc,x,xloc
nsel,r,loc,y,yloc

*if,yloc,eq,0,then
f,cnt,heat,pave/2*exp(-(xloc-xc/2)*(xloc-xc/2)/(2*sx*sx)-yloc*yloc/(2*sy*sy))
*else
f,cnt,heat,pave*exp(-(xloc-xc/2)*(xloc-xc/2)/(2*sx*sx)-yloc*yloc/(2*sy*sy))
*endif

!nsel,u,node,,ct
!*get,cnt,node,cnt,nxth
!cnt=cnt+1
```

```
*enddo
alls


nsel,s,loc,z,0
allsel,all

!f,all,heat,0
allsel,all

time,t+.001
deltim,.0002,.0001,.0002
timint,on,all
autos,on
lswrite,2
```

Removal of power & cool for 15.7 milliseconds

```
!remove bigauss distribution to nodes

/prep7

nsel,s,loc,z,0,mt
*get,nnodes,node,,count
*get,maxnode,node,,num,max
*get,minnode,node,,num,min
pave=0
*do,cnt,minnode,maxnode


*get,xloc,node,cnt,loc,x
*get,yloc,node,cnt,loc,y
nsel,s,loc,z,0
nsel,r,loc,x,xloc
nsel,r,loc,y,yloc

*if,yloc,eq,0,then
f,cnt,heat,pave/2*exp(-(xloc-xc/2)*(xloc-xc/2)/(2*sx*sx)-yloc*yloc/(2*sy*sy))
*else
f,cnt,heat,pave*exp(-(xloc-xc/2)*(xloc-xc/2)/(2*sx*sx)-yloc*yloc/(2*sy*sy))
*endif

!nsel,u,node,,ct
!*get,cnt,node,cnt,nxth
!cnt=cnt+1
*enddo
alls


time,t+.0167
deltim,.0005,.0005,.002
lswrite,3
```

Change node types to find out stress after ls2 (1 millisecond powerburst)

```
!This file obtains the mechanical solution from the thermal solution
!cumo2.inp3
finish
/filname,stress2-23
/prep7
etchg,tts
finish
/sol
lsclear,all
nsel,s,loc,y,0
d,all,uy,0

allsel,all

nsel,s,loc,y,d
d,all,uy
```

```
allsel,all

nsel,s,loc,z,0
nsel,r,loc,x,xc/2+xc/(2*v),xc/2-xc/(2*v)
nsel,r,loc,y,0
d,all,ux

allsel,all


nsel,s,loc,z,-fl
nsel,r,loc,x,xc/2+xc/(2*v),xc/2-xc/(2*v)
nsel,r,loc,y,0
d,all,ux
d,all,uz

allsel,all


!
save
ldread,temp,2,,.001,,finaldata,rth
antype,static,new
solve
```

References

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[3] Swain, T. High Performance Compact Absorber Devices, LBNL Engineering Note M7521, 1995